

## THE LOST SIBLINGS OF THE SUN

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## ABSTRACT

The anomalous chemical abundances and the structure of the Edgewood-Kuiper belt observed in the solar system constrain the initial mass and radius of the star cluster in which the sun was born to  $M \simeq 500$  to  $3000 M_{\odot}$  and  $R \simeq 1$  to  $3$  pc. When the cluster dissolved the siblings of the sun dispersed through the galaxy, but they remained on a similar orbit around the Galactic center. Today these stars hide among the field stars, but 10 to 60 of them are still present within a distance of  $\sim 100$  pc. These siblings of the sun can be identified by accurate measurements of their chemical abundances, positions and their velocities. Finding even a few will strongly constrain the parameters of the parental star cluster and the location in the Galaxy where we were born.

## 1. INTRODUCTION

It is commonly accepted that stars like the sun are born in clusters (Lada et al., 1993). The cluster in which the sun was born is long gone and the sun’s siblings are by now spread over the Galaxy. The structure of the hot Edgeworth-Kuiper belt objects provide evidence of this, as this population can be reproduced by a relatively nearby encounter with another star (Morbidelli & Levison, 2004). Such an encounter is expected to have occurred in the early history of the Solar system (Malhotra, 2008). The existence of a well organized planetary system, however, indicates that the parental cluster cannot have been very dense as otherwise a nearby passing star would also have perturbed the orbits of the planets.

Additional evidence for the sun’s dynamic history comes from the discovery of radioactive isotopes and their decay products in the proto-solar nebula (Hester et al., 2004), which is explained by a supernova explosion within 1.6 pc of the infant sun (Looney et al., 2006). The combination of arguments enables us to estimate the mass and size of the star cluster in which the sun was born. We follow the orbital evolution of these stars through the Galaxy for the lifetime of the sun and conclude that at least 1% (10 to 60) of the sun’s siblings should still be present within 100 pc, and more than 10% should be within about a kpc along the orbit of the solar system in the Galactic potential. With the Gaia satellite (Perryman et al., 2001) and ground-based searches the radial velocity and distance to the majority of the lost siblings will be determined, and the proper motion will be measured. These constrain the orbit of the proto-solar cluster and enable us to accurately determine the evolution of the Galactic potential and the birth place of the sun.

## 2. THE PARENTAL STAR CLUSTER

The sun and its eight planets were born about 4.57 billion years ago (Bonanno et al., 2002), probably in a star cluster, and it is in due time that our location in the Galaxy became so desolate. Evidence for this dynamic past comes from meteorite fossil records, where the presence of short-lived radioactive isotopes in primitive meteorites indicate that the 1.8 Myr young sun was polluted by a supernova explosion of a star about 15 to 25 times more massive than the sun within a distance of 0.02 to 1.6 parsec (Looney et al., 2006). Such a massive star lives for 6 to 12 Myr before it sheds the majority of its mass in a super-

nova explosion. This massive star must have formed some 4.2 to 10.2 Myr earlier than the sun. Such range in the distribution of stellar ages is also observed in the Orion Nebula where massive stars also tend to be a few to  $\sim 10$  Myr younger than the low-mass stars (Palla & Stahler, 1999).

The presence of a massive star close to the infant sun puts interesting constraints on its birth environment. Today, such a massive star is not even present within a distance of 100 parsec. By adopting a standard initial mass function (Kroupa & Weidner, 2003) about 1 in 400 stars is sufficiently massive to experience a supernova. Stars of  $m = 15$  to  $25 M_{\odot}$  are less common and would require a star cluster of  $M \gtrsim 500 M_{\odot}$  (Weidner & Kroupa, 2004).

Massive stars in a cluster tend to sink to the center in a fraction  $\propto 1/m$  of the two-body relaxation time scale ( $t_{\text{rlx}}$ ). If  $t_{\text{rlx}} \gtrsim 300$  Myr even the most massive stars are unlikely to have reached the cluster center by the time they explode. Massive stars in clusters with smaller  $t_{\text{rlx}}$  tend to populate the central region by the time they explode in supernovae, polluting the nearby young stars and proto planetary disks in the process (Wielen et al., 1996). Low mass stars, like the sun, are not strongly affected by mass segregation, and if such a star happens to be in the cluster core at the moment one star explodes it is likely to be still around when a subsequent supernova occurs.

We quantify this by performing a number of  $N$ -body simulations in which we initialized star clusters with a mass function and a Plummer sphere density distribution (Plummer, 1911) with radius  $R$  in parsec to track the number of supernovae that occurred within 1.6 pc of sun-like main-sequence stars. It turns out that the number of supernovae with one and the same star of  $0.8$  to  $1.2 M_{\odot}$  scales as  $N_{\text{nearbySN}} \sim 0.003 M/R$ .

A star cluster is a dynamic environment in which frequent encounters effectively ionize planetary systems (Malmberg et al., 2007). The passage of a star within a distance of  $r_{\text{enc}} = 100$  Astronomical Units (AU) can easily destroy the young protoplanetary nebula, leaving the sun without any material to form a regular planetary system (Hills, 1985; Kobayashi & Ida, 2001). If the planetary system is already formed such an encounter may induce high eccentricities and inclinations of their orbits, again resulting in strong perturbations which eventually leaves the sun with a reduced planetary system (Spurzem et al., 2006). The high eccentricities and inclinations observed in sev-

eral extra-solar planetary systems may be produced by such a relatively nearby encounter. The outer region of the solar system shows evidence for a relatively nearby encounter but not as close as 100 AU (Ida et al., 2000), an encounter at a distance within  $r_{\text{enc}} \simeq 10^3$  AU would be sufficient to explain the observed hot Kuiper belt objects, which have highly inclined orbits (Morris & O'Neill, 1988; Hester et al., 2004).

The requirement that the sun has not encountered another star at  $r_{\text{enc}} \lesssim 100$  AU, but is likely to have experienced an encounter within some  $r_{\text{enc}} \lesssim 10^3$  AU constrains the initial cluster density. We further require that the cluster survives long enough to warrant this encounter to occur before it dissolves. The dissolution time of a star cluster in the Milky Way Galaxy follows the empirical relation (Lamers et al., 2005)  $t_{\text{diss}} \simeq 2.3 \text{Myr } M^{0.6}$ . These constraints can be expressed in terms of cluster radius  $R$  (in parsec) and mass  $M$  (in  $M_{\odot}$ ), which we present in fig. 1. With estimates for the mass and the size of the parental star cluster we calculate that the velocity dispersion of the cluster must have been of the order of a km/s, which is comparable to the velocity dispersion in known young star clusters (Lada & Lada, 2003).

### 3. THE BIRTHPLACE OF THE SUN

The orbit of the solar system in the Galactic potential is almost circular, more or less in the disk. The orbital velocity is considerably higher than the velocity dispersion of the stars in the parental cluster. The cluster members are therefore unlikely to have drifted very far from the orbit of the sun around the Galactic center, but they may be at completely different locations along this orbit. The preservation of phase space in the dissolution of star clusters is used to study the merger history of the Galaxy (Helmi et al., 1999), but in this case we use the argument to find the lost siblings of the sun.

At the moment the sun is located at a distance of about 8.5 kpc from the Galactic center in the plane of the disk. The velocity is 10.1 km/s directed towards the Galactic center and 7.5 km/s away from the plane. The velocity perpendicular to the line-of-sight of the Galactic center is  $v_t = 235.5$  km/s in the rotation direction of the Galaxy, which is slightly ( $\sim 15$  km/s, since  $v_c \simeq 220$  km/s) higher than the local orbital velocity (Karachentsev & Makarov, 1996).

By calculating the orbit of the sun backwards in time, which can be achieved by inverting the current velocity vector, and integrating the equations of motion in the potential of the Galaxy for 4.6 Gyr, we can calculate the location in the Galaxy where the sun was born. With the parameters given and using a model for the Galactic potential (Paczynski, 1990) it turns out that the sun has been orbiting the Galactic center some 27 times since its formation, and was born in the  $\delta$ -quadrant at -1.39 kpc, 9.34 kpc and 25.3 pc along the galactic x, y and z-axis and with a velocity vector of -207, -48.2 and -6.72 km/s (see fig. 4). This birthplace is  $\sim 2.8$  kpc further out than the estimated distance to the Galactic center based on the relatively high metalicity of the sun (Wielen et al., 1996; Wielen & Wilson, 1997), but part of this metalicity argument could be explained by the early pollution of a supernova near the proto-solar nebula. Part (up to about half) of the other cluster members are also expected to be polluted by the same supernova, and their anomalous chemical characteristics can be used for the identification (Tolstoy et al., 2004).

It seems likely that the orbits of the sun and its siblings have been deflected by some small-angle scatterings on their long journey through Galactic disk. The radial distance over which

the sun may have been migrated by such scatterings can be as large as 2 kpc (Fuchs & Wielen, 1987), which interestingly is comparable to the range in radial distance for the orbit of the sun, as we present in Fig. 4. The radial velocity induced by such scatterings affect the orbit of all stars in the parent cluster and the effect on the number of nearby stars today is rather small. We quantify this by varying the current tangent velocity of the sun  $v_t$  and recompute the orbits of its siblings in the potential of the Galaxy assuming that the cluster dissolved 4.3 Gyr ago. The fraction of stars of the parent cluster that remain within 100 pc can then be expressed as a linear relation  $f(r < 100\text{pc}) \simeq 0.032 - 0.014(v_t/v_c)$ , and the fraction of stars within 1 kpc becomes  $f(r < 1\text{kpc}) \simeq 0.39 - 0.16(v_t/v_c)$ . These relations break down when  $v_t$  is either so small that the stars enter the Galactic bulge on their orbit, in which case the scattering becomes severe, or if  $v_t$  becomes sufficiently high that the stars escape the Galaxy.

The uncertainty in the current coordinates of the sun in the Galaxy will be magnified by computing its orbit back with time, making the location of birth uncertain. It turns out, however, that the exact place and velocity of birth are not crucial for our discussion, as the stars that were born together with the sun will be around wherever the sun was born. It is the orbits of those stars for which we integrate the equations of motion in time through the Galaxy to understand the dispersion in their position and velocity at a later time. The adopted model for the Galactic potential does not include spiral arms or local perturbations like star clusters and molecular clouds, which can have an appreciable effect on the calculated trajectories (Fuchs & Wielen, 1987; Quillen & Minchev, 2005). The uncertainties introduced by the model, however, have a minor effect on the relative position and velocities as all stars remain relatively close together in phase space throughout the integration and are therefore affected by variations in the potential in a similar fashion.

### 4. FINDING THE LOST SIBLINGS OF THE SUN

We pursue by constructing model star clusters that mimic the one in which the sun was born. These star clusters are assumed to dissolve along the trajectory of the sun in the Galaxy, shedding their stars in radial orbits with the escape speed of the cluster. In that way we are able to calculate the fraction of the stars from that particular part of the orbit that today are still in the vicinity of the sun. In Fig. 2 we present the fraction of stars that can be found in the solar neighborhood as a function of the moment that the star escaped from the parent cluster.

The fraction of brothers and sisters of the sun that are still within 100 pc of our current location in the Galaxy is about 1% if the proto-star cluster dissolved shortly after the formation of the sun, and the fraction increases to  $\sim 8\%$  if the cluster survived longer (see Fig. 2). The fraction of siblings within a kpc is at least  $\sim 10\%$ . The majority is located around the past and future orbit of the sun in the Galactic disk and within about 100 pc of the Galactic plane. This is a consequence of the relatively low velocity dispersion of the cluster compared to the orbital motion around the Galactic center.

Today, we should still be able to recognize the siblings along the orbital trajectory of the solar system in the Galaxy. If the sun happens to be on a different orbit this will reflect in the orbits of its siblings. The distribution of proper motions and distances of these stars are presented in Fig. 3 where we show the result from a cluster of 2048 stars with a 1 pc virial radius that dissolved 4.6 Gyr ago. The proper motions and distances

of these stars change in a characteristic way, indicated by the solid curve and in the direction of the two arrows.

The majority of our lost siblings are easily identified by the Gaia astrometric satellite or by ground based searches. We are still surrounded by them, even though they hide among millions of other ordinary looking stars. What enables us to recognize the other siblings are their orbital characteristics, which should be comparable to the sun. In Fig. 4 we present the distribution

of stars that once belonged to the proto-solar cluster; they are currently observable along the orbit of the sun in the Galaxy. The best place to look for the lost siblings is along the trajectory of the sun in the plane of the Galaxy, in leading and trailing orbits around the Galactic center. Identifying those stars will provide stringent limits on the sun's orbit around the Galactic center and gives us a unique window to study the conditions of the star cluster in which the sun was born.

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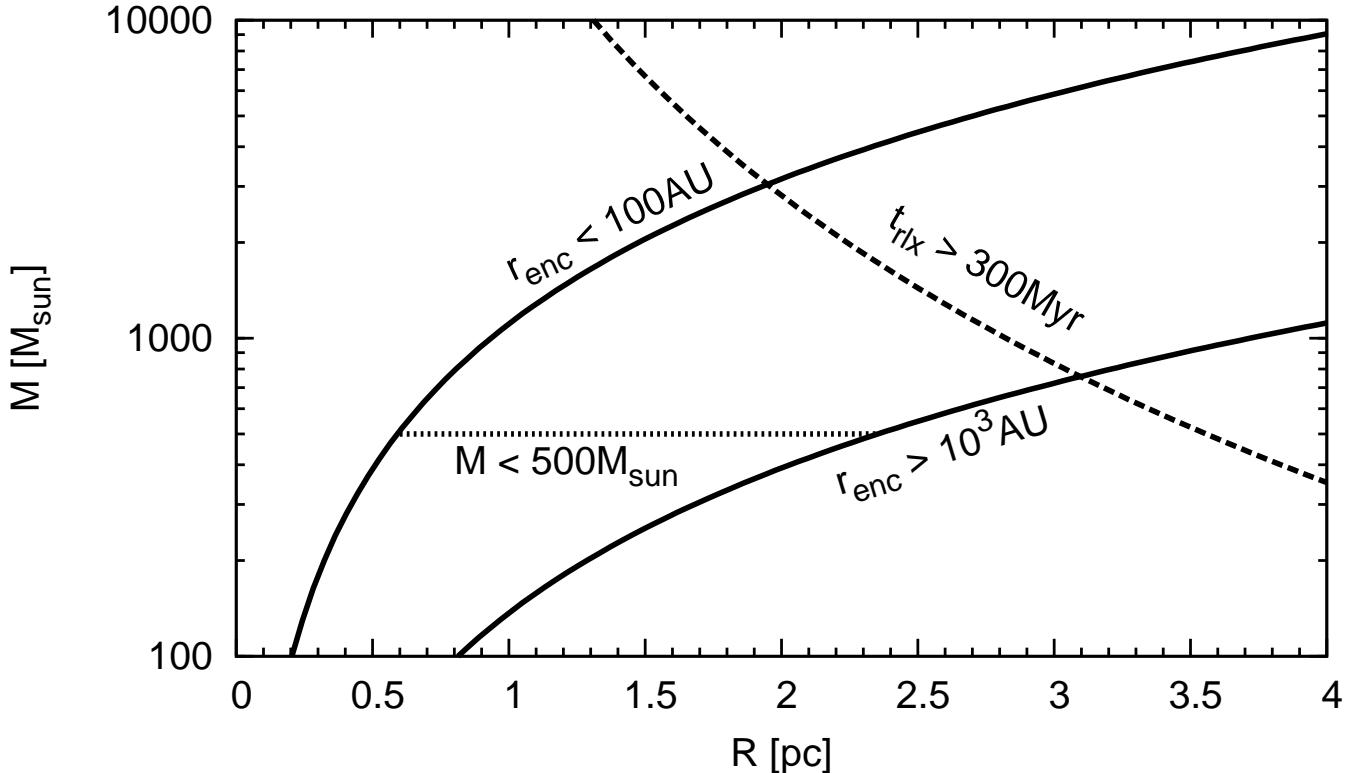


FIG. 1.— Constraints on the mass ( $M$  in  $M_{\odot}$ ) and radius ( $R$  in pc) of the cluster in which the sun was born. The allowed parameter space is fenced off by four curves, one for the minimum mass of about  $500 M_{\odot}$  (dotted line), one limits the relaxation time ( $t_{\text{relx}}$ ) to less than about 300 Myr (dashed curve), and two limiting the distance between which an encounter is likely to occur during the cluster lifetime (solid curves). If an encounter is expected outside  $r_{\text{enc}} = 10^3$  AU the orbits beyond Pluto are unlikely to have been affected, contrary to the observed high inclinations in the Kuiper belt (Ida et al., 2000). An encounter within  $r_{\text{enc}} = 100$  AU is likely to be destructive to the solar system as we know it (Adams et al., 2006). In order to warrant one or more close supernovae near the sun before the cluster dissolves we require that the relaxation time is smaller than 300 Myr. The area fenced off by the dotted, the dashed and the solid curves is the favorable range of parameters for the proto-solar cluster.

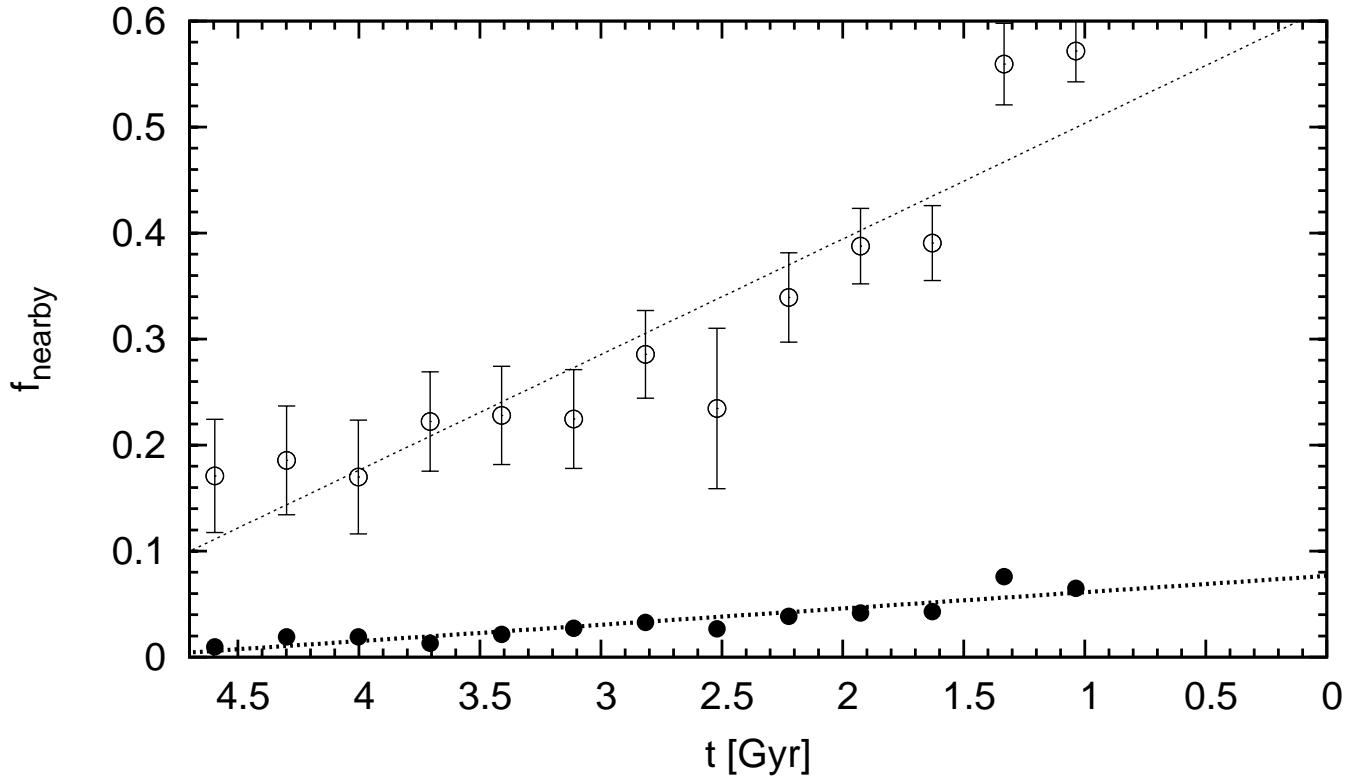


FIG. 2.— The fraction of siblings of the sun which are still in the neighborhood as a function of how long ago the parental cluster dissolved. The stars within 100 pc (bullets) and those within 1kpc (circles) are fitted by a straight line (dotted curves). The vertical error bars for the 1kpc calculations represent the one standard deviation from the mean and is based on calculating the trajectories of 2048 stars which were born in a virialized Plummer sphere with  $M \simeq 920 M_{\odot}$  and  $R = 1$  pc in the Galactic potential. The fraction of nearby siblings depends only weakly on the uncertainty in the current position and velocity of the sun.

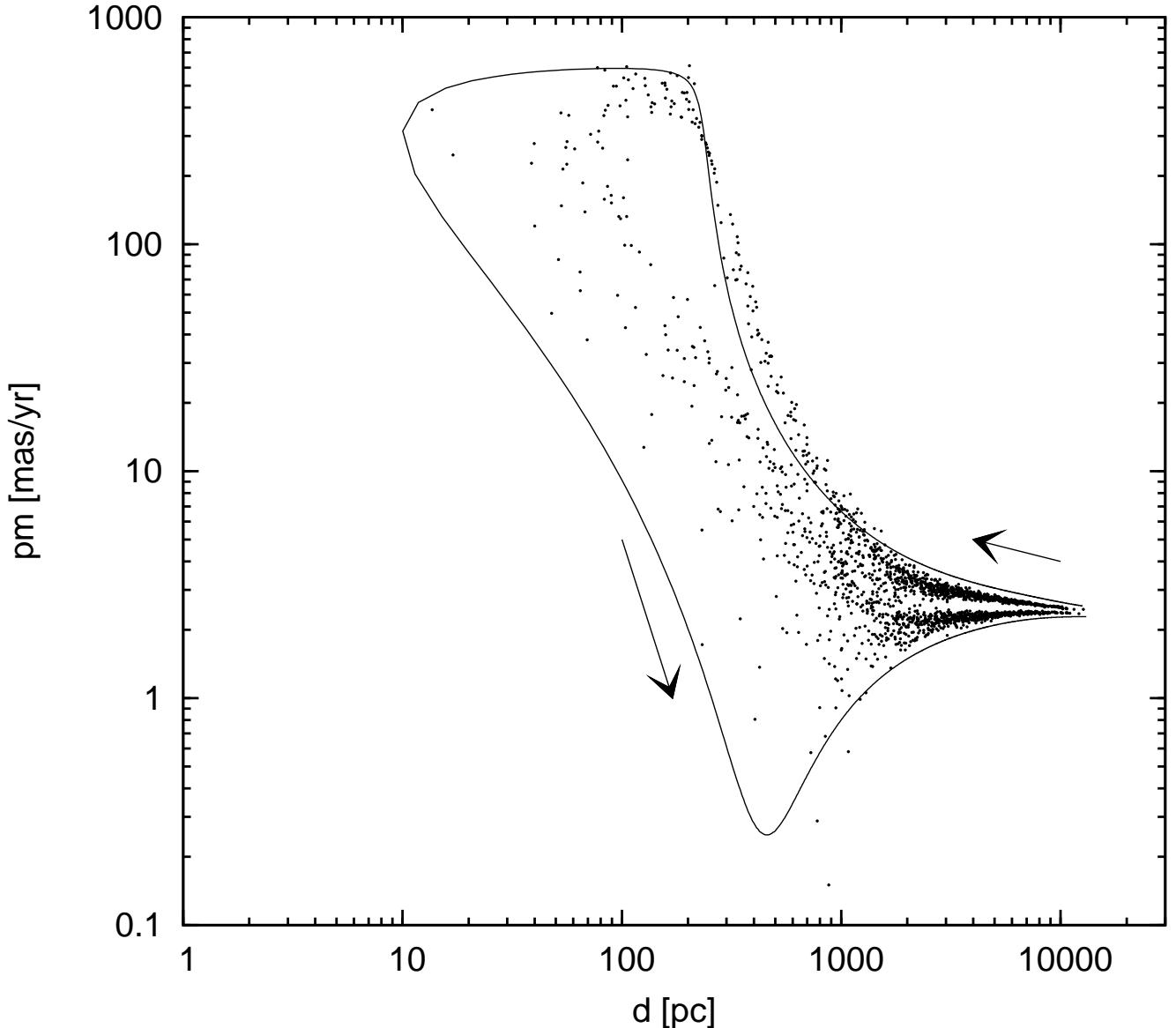


FIG. 3.— The characteristic pattern of the proper motion and distance of the stars in the solar neighborhood that once belonged to the same star cluster. In this case we assumed that the star cluster dissolved quickly upon the formation and pollution of the sun,  $\sim 4.6$  Gyr ago. The curve overplotted with the data points represent solar orbit with a slight offset of 10 pc along the x-axis and with a 10km/s higher velocity in the x-direction. The two arrows indicate how the distance and proper motion change with time for stars that approach the solar position (right arrow) or are ahead of the sun (left arrow).

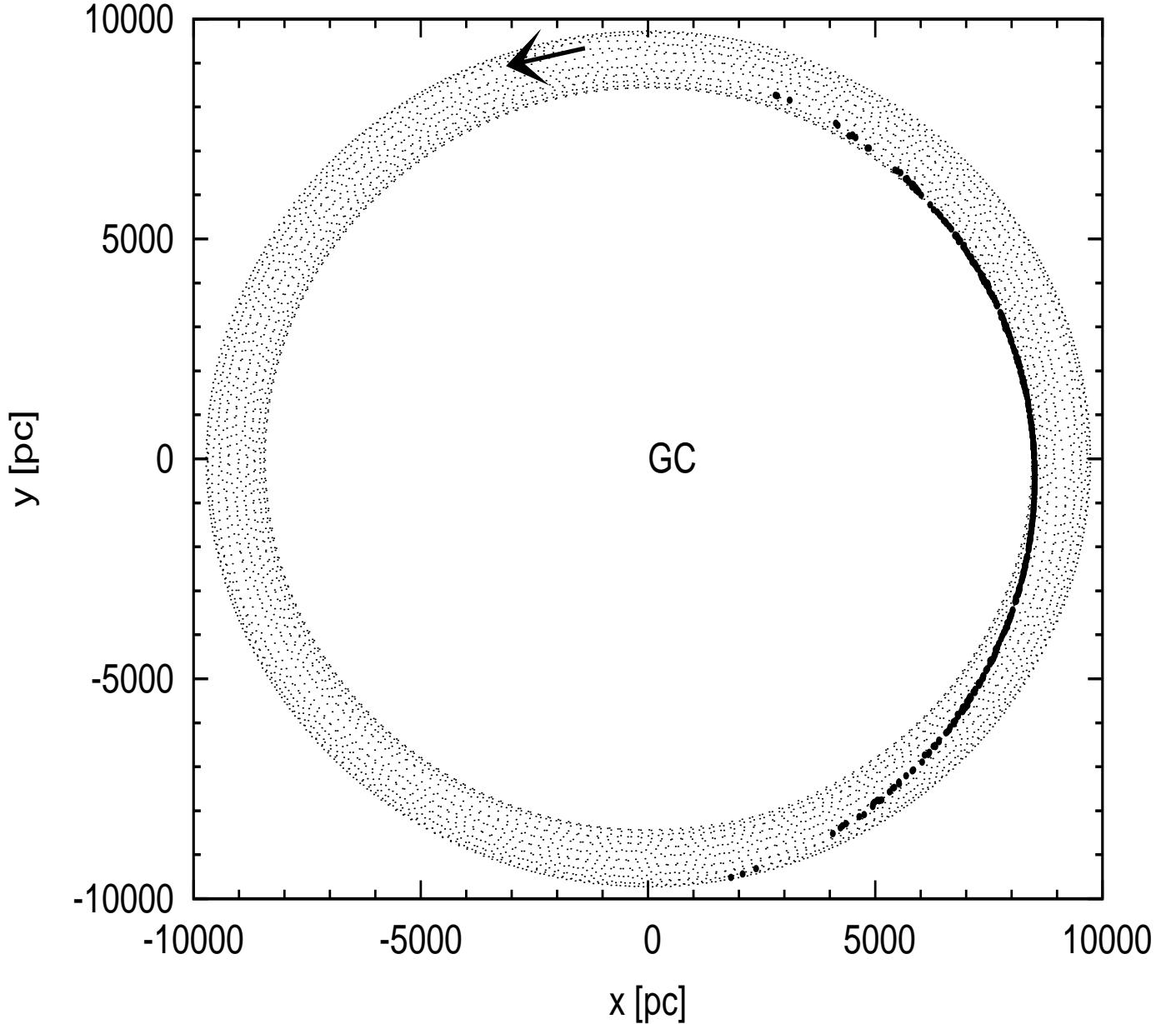


FIG. 4.— Top view of the Galaxy. The orbit of the sun for the last 4.6 Gyr is presented with the thin dotted curve, starting at the arrow. The sun is currently located at  $x = 8.5\text{kpc}$  with  $y = 0$ . A total of 1000 stars from a star cluster with the parameters used in Fig. 2 were followed together with the sun and evolved through time for 4.6 Gyr, their final positions are plotted as bullets.